Global Warming Potential

Life Cycle Assessment of District Heat Distribution in Suburban Areas Using PEX Pipes Insulated with Expanded Polystyrene

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Abstract

Goal, Scope and Background. Combined heat and power (CHP) is a strategy aimed at reducing the impact of the energy sector on the climate by more efficient use of the energy content of the fuel. The implementation of CHP requires the utilisation of the heat produced. Space heating by means of district heating is one possible use for such heat. In countries such as Sweden, where district heating is already extensively used, many multiapartment buildings are connected to district heating. For increased use, the distribution systems will have to expand into suburbs with single family homes. However, the environmental impact and cost of the district heat distribution system increase when the pipe networks are extended into such areas. This is due to the production and installation of longer pipe networks and increased heat losses from the system. Attempts have been made to find new types of pipe constructions in order to lower the costs of connecting single family homes to district heating. These should be evaluated from an environmental perspective. The EPSPEX system is a distribution system intended for suburban areas. This system consists of cross-linked polyethylene (PEX) pipes in insulating blocks of expanded polystyrene (EPS). This paper presents a life cycle assessment of the EPSPEX district heat distribution system. In a second scenario, sub-stations were added. The results indicate areas that require improvement and provide a basis for comparison with other types of district heat distribution systems.

Methods. Production, network construction and use of the district heat system were studied by means of life cycle methodology, employing specific data for the EPSPEX system and generic data for upstream impacts of the materials used. The system constructed in Vråen, Värnamo, Sweden, in 2002 was studied. The district heating used in Vråen is mainly based on biofuels. The functional unit was the use of one metre of an EPSPEX district heating system over a period of one year. The expected system life was 30 years. The results were characterised as global warming potential, acidification potential, eutrophication potential and the use of finite resources, as well as weighted by EPS 2000, ExternE and EcoIndicator 99. No external review was performed, but a reference group of district heating experts familiar with the practice has reviewed the study.

Results. Heat losses are clearly the main environmental impact in all characterisations and weightings (71–92% of the total impact), despite the fact that the heat production studied was mainly based on biomass combustion, generally perceived to be environmentally friendly. Of the system components, the production of EPS insulation blocks had the largest environmental impact.

Discussion. This impact, however, is compensated for by the fact that the need to produce less heat leads to a lower level of emissions. Several characterisation methods revealed that the production and combustion of diesel for excavating the pipe trench has a significant environmental impact. The jointing brass swaged coupling used for the PEX fluid pipes has a surprisingly high impact in terms of acidification and EPS 2000, considering the small amount of brass in the system.

Conclusions. The life cycle environmental impact is dominated by the heat production needed to compensate for heat losses from the system, despite the fact that the EPSPEX system is relatively well insulated compared to a conventional district heating system. It is possible to shut down the heating circuit and only use the hot tap water circuit during the summer months; this reduces the heat losses and is an advantageous feature of the system. The second largest environmental impact of the EPSPEX system arises from the production of the EPS insulation blocks. A decrease in nitrogen oxide emissions, especially those caused by the excavation and filling of pipe trenches, would be beneficial. A rough comparison has been made with available literature data for conventional DN25 twin pipes. The results indicate that the environmental impact of the EPSPEX system is probably lower. However, the pipes are not identical, as the water delivery capacity of the conventional pipe is slightly lower.

Recommendations and Perspectives. In Sweden, new types of pipes are being developed for district heating in suburban areas, and there is a need for an environmental comparison between such new alternatives and previous results for conventional polyurethane insulated steel pipes. This study reveals that biofuels, although perceived to be environmentally friendly, must be used with caution in order to ensure a satisfactory environmental performance. Heat loss from district heating should be minimized also when biofuels are used. The most immediate way to reduce such environmental impact is to increase the insulation. The environmental trade-off between lower heat losses achieved by the use of more insulation and the production of greater amounts of insulation material should be further studied.

Keywords: Combined heat and power (CHP); conventional DN25 twin pipe; district heat distribution system; EPSPEX; heat losses; LCA; low heat density areas; polyethylene pipes; polystyrene insulation; space heating

Introduction

The industrialised countries are striving to decrease their emissions of greenhouse gases by 5% (based on 1990 levels) by 2008/2012, in accordance with the Kyoto Protocol [1]. The corresponding figure for the European Union countries is 8%. In order to achieve this, it will be necessary to replace fossil fuels with biomass fuels and other renewable sources of energy. The European Commission's white paper for a community strategy and action plan proposes doubling the proportion of renewable energies in the gross domestic energy consumption of the European Union by 2010 (from the present 6% to 12%) [2]. Combined heat and power (CHP) generation is an important strategy for the efficient use of fuel in electricity production irrespective of whether fossil fuel or renewable energy is used [3]. The implementation of CHP requires that the heat produced is utilized. Space heating by means of district heating is one possible use for such heat. Where space heating is needed, district heating can contribute to eco efficient use of energy resources. In countries where district heating networks have been continuously expanded since the mid 20th century, a large proportion of multiapartment buildings are already heated by this system. 77% of multiapartment buildings in Sweden were connected to district heating systems in 2004 [4]. Thus, attention is increasingly focused on suburban areas with single family homes [5,6], where only 8% of the buildings are connected to district heating.

District heating has a market share of over 40% of the total space heating requirement of dwellings in Finland, Sweden and Denmark [7]. Germany has a considerably larger total district heat delivery, the largest of all European Union countries, but the market share is lower. District heating has an even higher market share in several central and eastern European countries.

The type of district heat distribution system most often used today consists of one district heating circuit with steel flow and return pipes, which are insulated with polyurethane and protected by an outer casing of polyethylene. In each connected house, heat exchangers transfer heat to the internal space heating circuit of the house and to the hot tap water. Life cycle assessments of conventional district heating systems have been previously described in a series of articles in this journal by Fröling et al. 2004 [8], Fröling and Svanström 2005 [9], and Persson et al. 2005 [10]. The heat losses from the system were shown to be of major importance for the total environmental performance of the district heating pipes.

The less densely built up an area is, the less appealing are conventional solutions for district heat distribution in both economic and technical terms. Longer pipe distances per unit of heat delivered makes network construction more expensive per customer, and the increased heat losses further contribute to this cost development. The increasing relative heat losses due to decreasing heat delivery per metre of pipe system correspond to an increasing environmental impact due to the need to produce more heat to compensate for these losses. Therefore, attempts have been made to find new types of pipe constructions in order to lower the cost of connecting single family homes to district heating systems. Such new types of pipe should be evaluated from an environmental perspective. The EPSPEX system studied herein is a distribution system intended for suburban areas.

A circumstance affecting the construction cost of conventional district heating systems is the many different, specially skilled workers required subsequently to joint the pipes, e.g. for welding the steel pipes to withstand the pressures in the system and for field foaming of the polyurethane foam in the pipe joints. The EPSPEX system is designed to overcome such drawbacks. It is a low pressure, secondary system in which all elements of construction work, including pipe jointing, can be carried out by the same workforce that excavated the pipe trenches. The capital cost (material and construction) for a short installation in Landskrona, Sweden, made with the purpose of testing the EPSPEX technology, was found to be 10–15% lower compared to the estimated cost for a conventional twin pipe installation [11]. According to the producer, later installions of systems similar to the one in Vråen have had capital costs about 20% lower compared to conventional twin pipe systems [12].

The EPSPEX system is composed of four fluid pipes of cross-linked polyethylene (PEX) in a block of expanded polystyrene insulation (EPS) (**Fig. 1**). The system consists of two circuits, one for space heating and one for hot tap water. A flow pipe and a return pipe in the space heating circuit are used during the cold months of the year. This circuit is closed down each summer when space heating is no longer required,

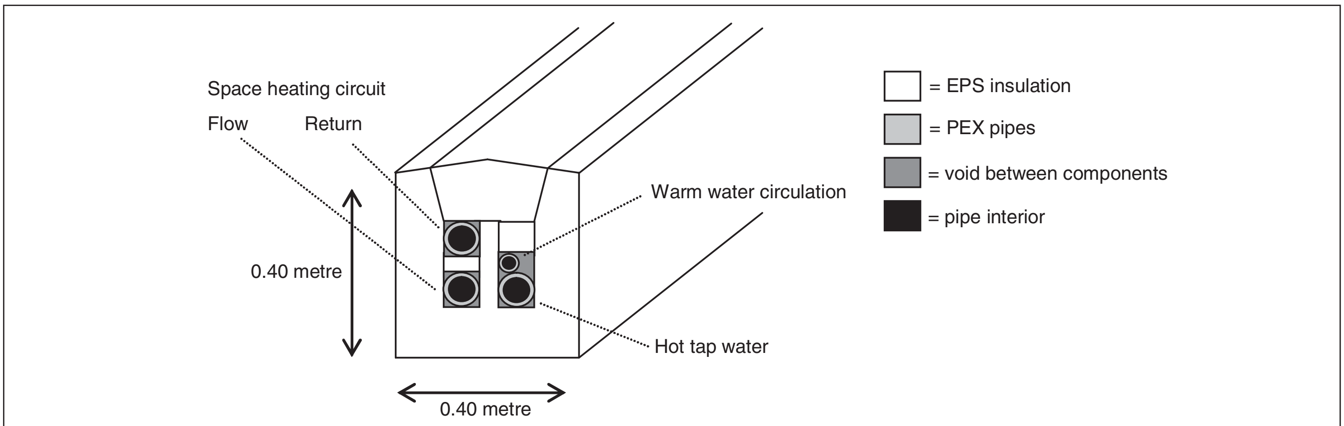

Fig. 1: Schematic illustration of the EPSPEX system. The two pipes to the left are the space heating circuit. The larger pipe to the right is for hot tap water and the smaller one for warm water circulation. Together they form the hot tap water circuit

thus minimizing heat loss. Hot tap water is provided all year round by a third pipe while a fourth pipe of lesser dimension, the warm water circulation (WWC) pipe, is used to recirculate a small amount of the hot water in order to maintain the temperature at the tap. The EPSPEX system is only suitable for use in dry ground above the ground water table, since the heat loss through the EPS insulation is very high if it becomes immersed in water [13]. The EPSPEX system has previously been studied as an alternative district heat distribution solution in terms of technical but not environmental performance [11,13,14].

This paper presents a life cycle assessment case study of production, network construction and use of the EPSPEX district heat distribution system as installed in Vråen, Sweden, in 2002. The district heating mix used in Vråen is mainly based on biofuels. The results of this study will provide a basis for comparison with other types of district heat distribution systems, e.g. conventional pipe systems [8–10].

1 System Description and Inventory

This case study covers production, construction and operation of an EPSPEX system for district heat delivery installed in the residential area of Vråen in Värnamo, Sweden, in 2002. The EPSPEX system is composed of four fluid pipes of cross-linked polyethylene (PEX) in a block of expanded polystyrene insulation (EPS) (see Fig. 1). The system consists of two circuits, one for space heating and one for hot tap water. A flow pipe and a return pipe in the space heating circuit are used during the winter months. This circuit is closed down each summer to minimize heat loss. The possibility of shutting down the space heating system does not exist in a conventional district heat distribution layout; this opportunity is for the EPSPEX system made possible by the centrally generated and separately delivered hot tap water. Two pipes of lesser dimensions, forming the hot tap water circuit, are used for delivery of hot tap water and warm water circulation all year round. The inventory data for the network construction and use refer to the Vråen system, with some additional data from a similar network constructed in Bromölla, Sweden, in the autumn of 2003.

The Vråen residential area includes 165 apartments in 17 houses [15]. This area was converted from direct electric heating to district heating in October 2002. The length of the total EPSPEX system in Vråen is 800 m. In the Vråen area, the total annual demand for space heating and hot tap water is 4.54 TJ, to which heat losses from the distribution system must be added.

Production of the EPSPEX system comprises two main parts; the production of the EPS insulating blocks and the production of the PEX fluid pipes. The insulating blocks and the pipes are transported separately to the construction site. During construction of the district heat distribution system, a pipe trench is excavated, and the EPS blocks are positioned in the trench and connected by means of small metal wedges, after which the PEX pipes are rolled out into depressions in the EPS blocks. The PEX pipes are jointed using brass swaged couplings. An EPS top cover is installed over the depressions in the insulating blocks containing the pipes, and a marker band is placed on top of the culvert before the trench is filled with the excavated material, from which stones have been removed. Heat is produced in a district heating plant and transported to Vråen and neighbouring areas in a transmission pipe. The transmission pipe is not included in this study. Central heat exchangers are used to transfer the heat from the water in the central pipe to the Vråen local EPSPEX system, where the water is circulated by means of pumps. In a second scenario, a sub-station in each house was added (heat exchanger and pump), to enable comparisons with systems where sub-stations are necessary. The general system description of the LCA activities involved in production, construction and use of the EPSPEX system is shown in **Fig. 2**.

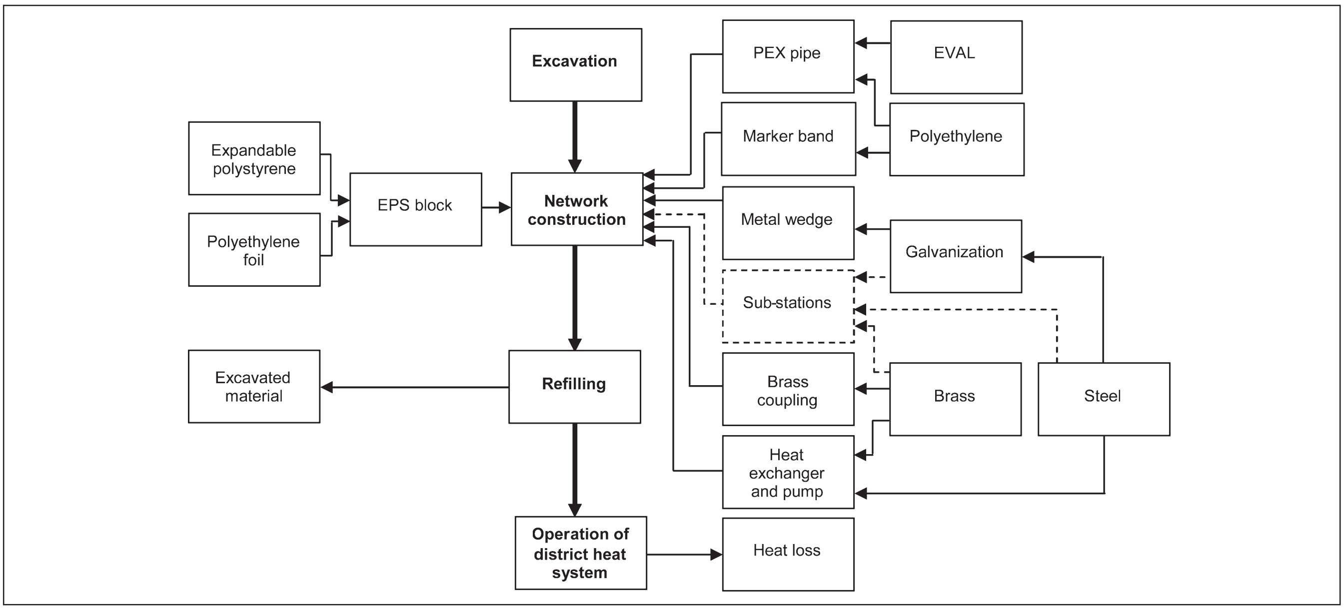

Fig. 2: Flow chart of the studied processes involved in the production, construction and use of the EPSPEX system. Transports are included in the studied system, but not shown as separate activities. To enable comparison with other district heat systems, sub-stations (dashed lines) have been studied in a second scenario

The functional unit in this study is one metre of EPSPEX system over one year. This functional unit facilitates comparisons with other district heat distribution systems, although it does not reflect the main function of the system, namely providing space heating and hot tap water.

The full inventory report is available in Swedish [16] from the commissioner the Swedish District Heating Association [17]. Capital goods and post use treatment of the EPSPEX distribution system have not been considered in this study. The use of land and water as resources, the impoverishment of renewable energy sources, the working environment, toxicological and ecotoxicological effects, and effects on biological diversity have not been separately considered in this study. The results of this study are case specific. No external review has been performed, but a reference group of district heating experts familiar with the practice has reviewed the study.

The investigated product system is outlined in Fig. 2. Many of the boxes in the figure represent underlying systems of activities. Data for the main activities have been gathered from practitioners. For up- and downstream activities and sub systems, generic and average data from the literature have been used. The LCAiT 4.1.7 Life Cycle Inventory Tool was used to handle the inventory information [18].

Inventory data for the different activities in the system are presented in Sections 1.1–1.8. The addition of sub-stations in the second scenario is presented in Section 1.9. Inventory information common to several subsystems (e.g. vehicle emissions, energy generation and fuel production) is described in Section 1.10.

1.1 PEX pipes

The PEX pipes are made of cross-linked polyethylene. The average dimensions of the pipes used in Vråen have been studied (1.4 kg/m EPSPEX system) [12]. The district heating water pipes (one flow and one return) are PEX 40 (40 mm outer diameter, 3.7 mm thick walls) with ethylvinylalcohol (EVAL) as a barrier to prevent oxygen diffusing into the circulating water (0.4 mm inside layer). The hot tap water pipe is PEX 40 (40 mm outer diameter, 5.5 mm thick walls) while the warm water circulation pipe is PEX 22 (22 mm outer diameter, 3.0 mm thick walls, 0.19 kg/m). PEX 40 is delivered as 50 m rolls and PEX 22 as 150 m rolls. PEX pipe production data are described as the production of high density polyethylene pipes using generic data from three Dutch production sites [19]. The PEX pipes used were produced in Stenungsund, Sweden, and transported by truck to Västerås (450 km). EVAL has been included as an increased use of polyethylene in the pipes. EVAL is produced in Japan and transported by freighter to Göteborg (21000 km) and then by truck to Västerås (450 km). The environmental impact of the EVAL coating process in Västerås has not been considered. The finished PEX pipes are transported by truck from Västerås to Vråen (500 km).

1.2 EPS blocks

The EPS blocks are produced from expandable polystyrene by Dorocell AB in Täby, Stockholm, Sweden. The blocks are 0.4 m high, 0.4 m wide and 3 m long (0.16 m^3/m EPSPEX system, 4.8 kg/m EPSPEX system) and wrapped in polyethylene foil. Parts of the blocks are cut away to provide space for the PEX pipes. The EPS waste could be recycled but this has not been considered in this study. EPS production data represent an average value from 12 production sites in western Europe [19]. The blowing gas pentane is released (0.05 kg/kg EPS block) during the blowing of the EPS to blocks [20]. Furthermore, electricity (1.6 MJ/kg) and light fuel oil (3.4 MJ/kg) are consumed [21]. EPS is produced in Belgium and transported to Täby by truck (1200 km), where it is expanded into blocks. Data for the production of polyethylene foil (0.01 kg/kg EPS block [20]) were an average of 8 production sites in the United Kingdom [19]. Polyethylene foil is produced in Stenungsund and transported by truck to Vråen (500 km). The finished EPS blocks are transported from Täby to Vråen by truck (500 km).

1.3 Marker bands

Marker bands are used for marking and identification when laying pipes. The marker bands are made of high density polyethylene (0.012 kg/m EPSPEX system). Data for the production of high density polyethylene were based on the European average for 1990–1993 [22]. The marker bands are produced in southern Sweden and transported to Vråen by truck (300 km).

1.4 Brass couplings

Brass swaged couplings are used to joint the PEX pipes. Average coupling dimensions have been estimated; T-couplings for PEX 40 (1.0 kg/coupling) and PEX 22 (0.27 kg/coupling) [12,23]. Brass swaged coupling production data (0.080 kg/m EPSPEX system) have been estimated based on the production of copper [24]. The couplings are produced in Germany and transported to Vråen by truck (1000 km).

1.5 Metal wedges

Metal wedges of galvanized steel are used to connect the EPS blocks. Steel production data are based on an average for 14 European production sites [25]. Electricity (540 MJ/kg steel) and light petroleum gas (280 MJ/kg steel) are used for galvanization [26]. In average, one wedge is needed for every metre of the EPSPEX system (0.053 kg wedge/m) [12]. Galvanized steel is produced in Borlänge in northern Sweden and transported by truck (560 km) to Genevad in southern Sweden, where the wedges are produced, after which they are transported by truck to Vråen (200 km).

1.6 Excavation, network construction and refilling

The environmental impact from excavation depends on the type of soil and amount of stones as well as the quantity of asphalt, electrical cables etc. in the area where the district heat distribution system is constructed. The Vråen area was relatively easy to excavate. The 1 metre deep by 1 metre wide pipe trench was excavated using a compact excavator. The average amount of diesel needed to excavate and refill the trench was 1.0 litre/m EPSPEX system (18 MJ/m EPSPEX system for excavation and 18 MJ/m EPSPEX system for refilling) [12,27]. Stones and excavated material (320 kg/m

EPSPEX system) had to be removed by light truck (10 km). Waste treatment of this excavated material has not been considered, as such material can generally be reused. The need for other machines, for example, surface compactors, has not been considered in this study.

1.7 Central heat exchanger and pumps

Heat exchangers are used (two double plate heat exchangers, 60 kg and 40 kg, stainless steel) to heat exchange the water from the central transmission pipe to the EPSPEX system of the Vråen area [28]. Four pumps are used to circulate the water in the system (5 kg each, cast iron) [29]. The heat exchangers and pumps (total 0.15 kg heat exchangers and pumps/m EPSPEX system) are produced in Germany and transported to Vråen by truck (1000 km) [28]. Data for the production of steel and cast iron are based on the average for 14 European production sites [25].

1.8 Operation of the district heating system

The EPSPEX system is newly developed and there are to date no long-term measurements of the heat loss. Discussions about heat losses from an EPSPEX system installed in December 2001 in Landskrona, Sweden, [11] and the system installed in Vråen [14] have been presented. Studies of the performance of the system after repeated immersion in water have also been reported [13]. The heat loss increases dramatically during immersion (performance close to an uninsulated pipe when the insulation is water filled), and the heat loss for the dry insulation also increases after repeated soaking. Heat losses in laboratory studies have been reported to increase with 43% after repeated soakings of the insulation, recovering to about 20% when followed by a dry up period [13]. Thus the EPSPEX system is only suitable for use in dry ground above the ground water table. The effect was less pronounced for insulating blocks made from EPS foam with a lower density than in this study.

The heat losses reported here have been determined according to the model described in [14]. Results for pipes with slightly larger dimensions than the average in Vråen (somewhat overestimating the heat losses) were provided by Tommy Persson, Lund University of Technology [30], using material data for EPS blocks that had never been exposed to water (somewhat underestimating the heat losses). The modelled heat loss should preferably be validated in relation to long-term measurements but in the absence of such measurements, the model results have been used.

Heat loss depends on the season. During winter, all four pipes are used, while during summer, only the hot tap water circuit is in operation. During spring and autumn, the temperature of the space heating pipes (T_{rad}) is somewhat lower than during winter. In **Table 1**, temperature information [31] and heat losses [30] are shown.

The total annual heat loss amount to 305 MJ/m EPSPEX system (average annual heat loss of 9.7 W/m). The Vråen system contains 800 m of EPSPEX system, giving a total annual heat loss of 0.25 TJ (approximately 5% of 4.54 TJ delivered heat). As a means of comparison, it should be mentioned that the average annual heat loss from a conventional DN25 twin pipe is around 14 W/m (calculated from Table 4 in [10]). If the space heating circuit had been used for a longer period of the year, e.g. because of a very chilly period during the summer, the heat loss from the Vråen EPSPEX-system would be higher. A fifteen days longer spring or autumn period would increase the annual heat loss with about 2%. There should be no dramatic change in the outcome if the chilly days happened in the middle of the summer period; since the EPSPEX system is a secondary system (small water volume to displace) there is no prolonged delay when starting up the space heating circuit.

1.9 Second scenario: Sub-stations

In today's most common type of district heat distribution system, each house is equipped with a sub-station, a set of heat exchangers and regulation equipment to transfer heat from the district heating system to the local heating system in the house. This heat delivery method was not used in Vråen, where the heating system and radiators in each house were directly connected to the district heating system. The EPSPEX system can be used in both ways. To enable comparisons with district heating systems using sub-stations, substations were included in a second scenario. The sub-stations are produced of galvanized steel (39 kg), iron (3 kg), copper (1.5 kg) and plastics (1.5 kg) in Helsinge, Denmark [32]. Each sub-station weighs 45 kg and a total of 17 are needed (0.96 kg sub-station/m EPSPEX system). Steel production data were based on an average of 14 European production sites [25]. Electricity (540 MJ/kg steel) and light petroleum gas (280 MJ/kg steel) are used for galvanization [26]. It has been estimated that the environmental impact of iron is the same as that of steel. Steel is produced and galvanized in Borlänge and transported to Helsinge by truck (800 km). Copper production data have also been included [24]. Copper is produced in Germany and transported to Helsinge by truck (500 km). High density polyethylene production data have been applied to the production of plastics [19]. Plastics are transported by truck (200 km) and the completed sub-station is also transported by truck to Vråen (200 km).

Table 1: Temperatures of the flow and return pipe of the space heating circuit ($T_{rad,flow}$ and $T_{rad,return}$), of the hot tap water pipe ($T_{hot\ water}$) and of the warm water circulation pipe (T_{WWC}) together with total heat losses of the EPSPEX system during the four seasons [30,31]

	Dates	Days	$T_{rad,flow}$ (ºC)	$T_{rad,return}$ (ºC)	$T_{hot\ water}$ (ºC)	T_{WWC} (ºC)	Heat loss (W/m)
Winter	Dec 1–March 19	109	80	40	60	55	**13.6**
Spring	March 20–May 16	58	50	40	60	55	**10.2**
Summer	May 17–Sep 19	126	closed		60	55	**5.8**
Autumn	Sep 20–Nov 30	72	50	40	60	55	**10.2**
						Annual average (time weighted):	**9.7**

1.10 Generic Inventory information

Electricity (for rail transport and other processes) is based on average Swedish electricity generation (mainly 47% hydro and 47% nuclear) [33]. Nuclear electricity is reported in some datasets referring to plastic production [19,22], but no nuclear waste is reported. Nuclear electricity generation has been added to such data sets [33]. District heat production for use in Vråen in 2002 was based on a mixture of biofuels 80%, light petroleum gas 15%, light fuel oil 3% and landfill gas 2% [34]. The electricity for circulation pumps and regulation equipment has not been taken into account. Production data for diesel oil, heavy fuel oil, light fuel oil and light petroleum gas includes oil extraction, transport, refining, and distribution [35]. No environmental effects due to the production of landfill gas are considered. All truck transport concerns heavy trucks (highway), maximum load 40 tons, maximum weight 60 tons, 70% load, Euro2 unless otherwise stated, and emission factors have been used [36]. Emission factors have also been used for transport using light trucks (urban areas, maximum load 8.5 tons, maximum weight 14 tons, 50% load, Euro2) and freighters (>8000 dead weight tons, 60% load) [36]. The emissions of a compact excavator were modelled using data for diesel combustion in a forestry machine [37]. Emission factors for combustion of light fuel oil in the production of district heat in Vråen and the blowing of EPS are based on combustion in small boilers (10–100 kW) [35]. Emissions from the combustion of the light petroleum gas used for galvanization are calculated from data on the combustion of light petroleum gas in an industrial manufacturing process [38]. Emissions from the combustion of landfill gas for district heating in Vråen are based on the combustion of natural gas, but with no fossil carbon dioxide emissions since this carbon would eventually have been emitted to atmosphere disregarding management practice [35]. The emissions from the combustion of biofuels for heat production are based on data on emissions from the combustion of wood chips [39].

2 Results and Discussion

The inventory results have been characterised as global warming potential (GWP) [40], acidification potential (AP) [40], eutrophication potential (EP) [40] and use of finite resources (Resource) [41]. Three weighting methods have also been used; EPS 2000 [42], ExternE [43] and EcoIndicator 99 [44].

The results of this study are applicable to the district heating system in Vråen, Sweden, under the conditions described in this paper. The results are based on the functional unit one metre of EPSPEX system in use for one year, with an expected system life of 30 years.

The results pertaining to heat loss, EPS block, PEX pipe, network construction and heat exchanger and pump are reported separately. Heat loss refers to the energy needed to produce extra heat to compensate for losses. Raw material extraction, production and transport are included under the heading 'EPS block', and this is also the case for the 'PEX pipe' and the 'Heat exchanger and pump' headings. Network construction includes trench excavation and transport of excavated material in addition to the production of metal wedges, metal swaged couplings and marker bands.

To gain an understanding of how a changed system setup would affect the environmental impact, the impact of the sub-stations has been studied and presented as a second scenario for the four selected characterisation methods).

2.1 Inventory results

Selected inventory parameters for the five system parts are presented in **Table 2**. The full inventory matrix (in Swedish) can be found in Johansson et al. 2005 [16].

For most of the parameters listed in Table 2, the compensation for heat loss predominates, despite the fact that district heat is mainly generated from biofuels. The largest amount of waste is produced during the trench excavation. The excavated material can usually be put to other uses.

Table 2: Selected inventory information pertaining to the EPSPEX system (g/m EPSPEX system, year)

		Heat loss	EPS block	PEX pipe	Heat exchanger and pump	Network construction
Resource use	Crude oil	1600	140	54	0.33	38
	Natural gas	69	160	25	0.19	2.4
	Hard coal	37	16	7.8	3.0	3.0
	Lignite	34	3.9	0.78	0.0011	0.62
	Iron	–	0.15	0.079	7.2	2.5
Emissions to air	CO_2	4600	470	110	9.8	130
	SO_2	9.3	1.7	0.87	0.013	0.47
	CO	9.4	0.29	0.060	0.15	0.64
	NO_x	28	2.1	0.65	0.014	2.1
	N_2O	15	< 0.01	< 0.01	< 0.01	< 0.01
	NMVOC [a]	13	0.14	< 0.01	< 0.01	0.46
Emissions to water	COD [b]	0.036	0.11	0.011	0.0014	0.0073
Waste	Excavated material	–	–	–	–	11000
	Non-hazardous waste	370	13	6.5	1.1	980
	Hazardous waste	1.7	0.17	0.38	< 0.01	0.044
	Radioactive waste	0.0074	0.0040	0.0025	< 0.0001	0.00014

[a] Non-methane volatile organic compounds
[b] Chemical oxygen demand

2.2 Characterisations

Inventory results from the EPSPEX system were characterised into global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and use of finite resources (Resource), and presented in **Fig. 3**.

The largest contribution to greenhouse gas emissions (total impact of 10 kg CO_2 equivalents/m EPSPEX system, year) arises from the production of extra heat needed in order to compensate for heat loss (92%), irrespective of the fact that more than 80% of the heat produced in district heating systems is generated by means of biofuels. The second largest impact arises from the production of the EPS blocks. This was not unexpected, as EPS blocks are the heaviest component and produced from non-renewable resources.

The results for acidification potential and eutrophication potential are similar to the global warming potential results (total impact of 0.036 kg SO_2 equivalents/m EPSPEX system, year and 0.045 kg NO_3^- equivalents/m EPSPEX system, year, respectively) and heat losses are predominant (87% and 85%, respectively). However, network construction contributes a relatively larger proportion, especially during excavation, due to nitrogen oxide emissions. The sulphur dioxide emissions from the production of the brass swaged couplings are also significant in terms of acidification potential.

For the use of finite resources (weighted together with the resource to use ratios, total impact of 0.051 kg resource equivalents/m EPSPEX system, year[2]), heat losses are predominant (82%). The largest contribution to the use of finite resources is attributable to the moderate amounts of fossil fuels used in the Vråen district heat generation (light petroleum gas 15%, light fuel oil 3%) when compensating for heat losses. Other district heat production methods, such as residual heat, would lead to a marked decrease in environmental impact. The production and transport of the EPS blocks have a larger relative impact compared to the other three characterisations, due to the raw material utilized and the energy resources required for production. The production of the heat exchanger and pump also has a larger relative impact regarding the use of finite resources, due to the consumption of virgin iron.

Heat loss from the EPSPEX system constitutes an important part of the environmental impact irrespective of the characterisation method used. Increased thickness of the EPS insulating blocks would therefore reduce the environmental impact of the system without the impact caused by increased production exceeding that of the gain.

In order to illustrate more clearly how the environmental impact is distributed among system parts other than heat loss, the results of the characterisations of the different system parts and the excavation are listed in **Table 3**.

Of all the system components, the EPS block makes the largest contribution to global warming. This is mainly due to high carbon monoxide and methane emissions from the polystyrene production activity. The global warming impact of excavation is lower in this study compared to what could be expected from previous studies of district heating systems [9]. The main reason for this is that compact instead of large excavators were used and that the site was more easily excavated (limited amount of rocks, pipes, cables etc) in this case study compared to conditions described in earlier studies [9]; thus the diesel consumption per metre of pipe trench was lower.

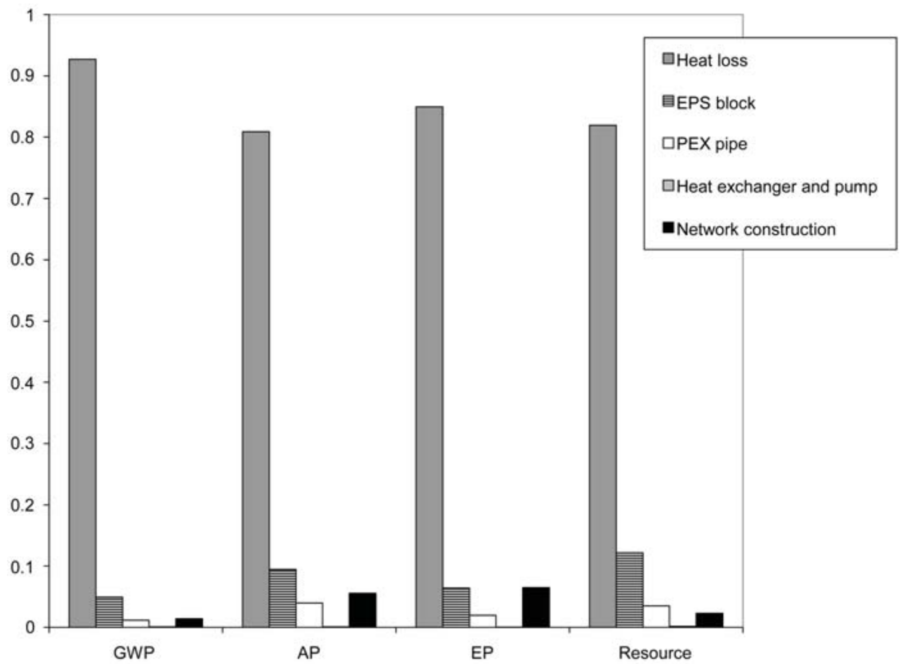

Fig. 3: Compilation of EPSPEX system characterisations based on inventory results (including heat loss during use); global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and use of finite resources (Resource). The results have been divided into five separate parts: heat loss, EPS block, PEX pipe, heat exchanger and pump, and network construction. The total result for each characterisation is arbitrarily set to one

Table 3: Characterisation results from the construction of the EPSPEX system (heat loss during operation is not included). In the second scenario, sub-stations in each building were added. Please note that sub-stations are not included in Fig. 3

	Global warming potential ($g\ CO_2$ eq./m, year)	Acidification potential ($g\ SO_2$ eq./m, year)	Eutrophication potential ($g\ NO_3^-$ eq./m, year)	Use of finite resources (g resource eq./m, $year^2$)
EPS block	510	3.4	2.9	6.2
PEX pipe	120	1.4	0.88	1.8
Heat exchanger and pump	10	0.024	0.021	0.080
Marker band *	0.37	0.0063	0.0053	0.014
Metal wedge *	3.5	0.0082	0.0073	0.028
Brass coupling *	6.8	0.39	0.076	0.088
Excavator *	100	1.4	2.5	0.79
Transport excavated material *	23	0.17	0.29	0.17
Total	**780**	**6.8**	**6.7**	**9.2**
Sub-station: Second Scenario	64	0.32	0.17	0.54
Total: Second Scenario	**840**	**7.1**	**6.9**	**9.7**

* Activities included in 'network construction' in Fig. 3

When comparing the emissions of acidifying compounds from the production of the different system components and from the excavation, the environmental impact of the excavation is almost as large as that caused by the production and transport of the EPS blocks. This is due to nitrogen oxide emissions from the excavators. The production of the brass swaged coupling has a relatively large impact connected to copper production; probably since copper from sulphide ore leads to large emissions of acidifying sulphur dioxide and nitrogen oxides. The magnitude of this impact is remarkable considering the small amount of brass used per metre in the EPSPEX system. Couplings made from recycled brass or other materials would lead to reduced emissions. During the production of the EPS blocks, the emissions of nitrogen oxides to air and acidifying compounds to water from the polystyrene production were responsible for the largest contributions to acidification.

The contributions to eutrophication from the system components and the excavation are similar to the contributions to acidification. Also here, excavation causes almost as large an impact as the production and transport of the EPS blocks. Emissions of nitrogen oxides from excavation and polystyrene production contribute most to eutrophication. A further decrease of excavation necessary (smaller pipe trenches) would together with choosing low-emitting work machines reduce the contribution to eutrophication. The excavation has a larger relative impact on eutrophication compared to acidification. In contrast, the brass coupling has a lower relative impact.

The characterisation into use of finite resources showed very similar results to those for global warming, with only marginal differences. When comparing the use of finite resources associated with the different system components, the production and transport of the EPS blocks has the largest environmental impact. This is due to the use of crude oil and natural gas as a raw material and energy source for polystyrene production. Crude oil and natural gas are resources that are consumed relatively quickly in relation to the known reserves and therefore have a high relative impact.

The sub-stations added to the heat delivery system in the second scenario increases the characterisation results for the construction related activities (i.e. all except heat losses during operation) by 3–8%, see Table 3.

2.3 Weightings

Weighting results from EPS 2000, ExternE and EcoIndicator 99 are presented in **Fig. 4**. EPS 2000 is a Swedish method that uses economic values to weigh together different categories of environmental impact [42]. The ExternE method was developed in a European Union project for the evaluation of energy production facilities and focuses on the external costs of the energy companies [43]. EcoIndicator 99 is a Dutch method that weighs together the impact on human health, ecosystem quality and resources [44].

When weighting according to the EPS 2000 method (total impact 3.2 ELU/m EPSPEX system, year), the heat loss has the largest environmental impact, mainly due to emissions of particulate matter, carbon dioxide and nitrous oxide. The second largest contributor is network construction, where the production of the brass coupling has a large impact, as the method is emphasising the use of finite resources. Production of the EPS blocks has a considerable impact due to the use of natural gas. The heat exchangers and pumps have the largest relative impact due to their use of finite resources, mainly iron ore.

Weightings in accordance with ExternE (total impact 3.2 SEK/m EPSPEX system, year) and EcoIndicator 99 (total impact 0.52 Ecopoints/m EPSPEX system, year) show similar results for the distribution of the environmental impact between the system parts. Carbon dioxide, nitrogen oxide and nitrous oxide emissions from the production of additional heat to compensate for heat losses in the district heating system are responsible for 87 and 83% of the environmental impact, respectively. According to these methods, the activity that causes the second largest impact is the production of the EPS blocks, due to emissions of carbon dioxide and the consumption of crude oil and natural gas.

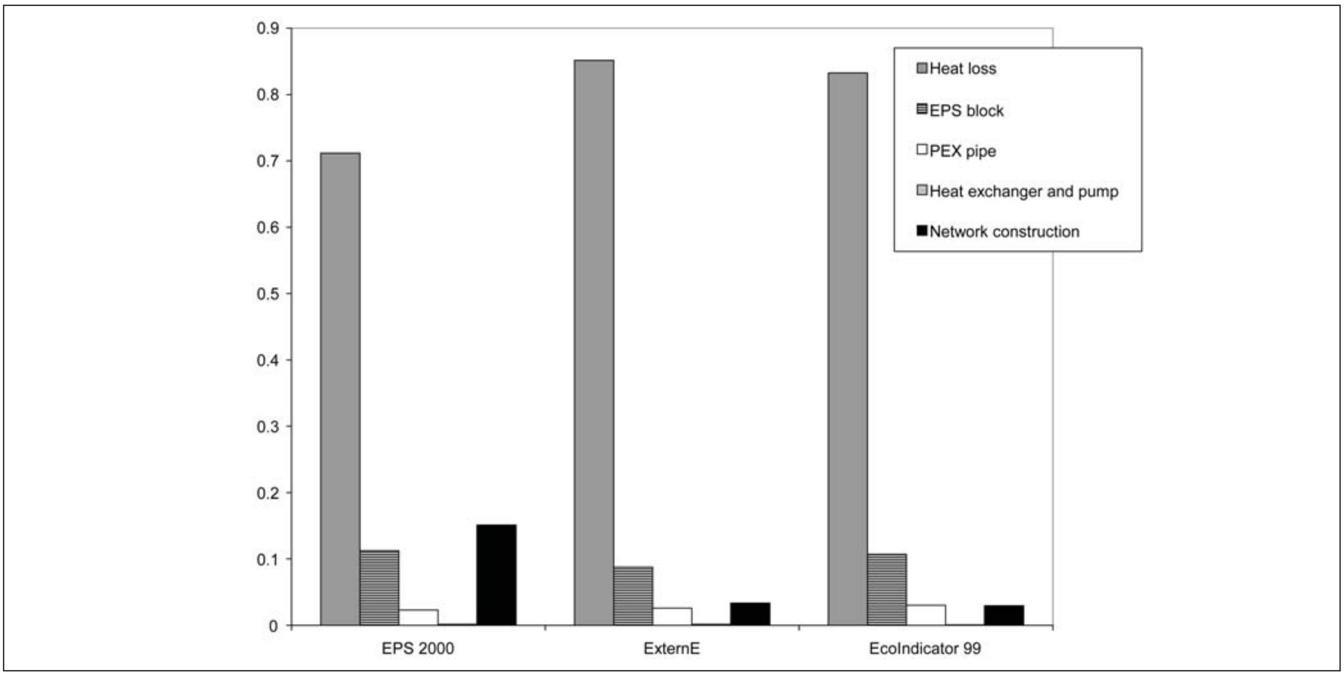

Fig. 4: Compilation of EPSPEX system weightings based on inventory results (including heat loss during operation); EPS 2000, ExternE and EcoIndicator 99. The results have been divided into five separate parts: heat loss, EPS block, PEX pipe, heat exchanger and pump and network construction. The total result for each characterisation is arbitrarily set to one

2.4 General discussion

The additional district heat generated to compensate for heat loss is shown to have a major environmental impact by all characterisations and weighting methods used.

The heat loss from the EPSPEX system in Vråen amounted to approximately 5% of the delivered heat. This is lower than many conventional district heating systems. Long-term performance studies are still needed to validate the calculated long-term heat losses from the EPSPEX system. For the EPSPEX system reported here, the heat loss from the transmission pipe connecting the production site to the Vråen area is not included.

Life cycle assessments of conventional district heating pipes (steel tubes with polyurethane insulation) can be found in the literature [8–10], but these do not include pipe dimensions with an heat delivery function identical to the EPSPEX system reported here. A DN25 twin pipe is the closest match, but has a lower maximum heat delivery capacity. In **Table 4**, a rough comparison of the results for these two pipe systems is presented. This comparison indicates that the EPSPEX system may make a lower contribution to the assessment methods discussed (eutrophication potential, EPS 2000 and ExternE were not reported in earlier studies), but final conclusions should not be reached until a more detailed comparison has been carried out. Heat loss and sub-stations are not included in the comparison in Table 4.

Regarding heat loss, the heat generation reported in the DN25 twin pipe study [10] does not correspond to the heat generation in Vråen, which is mainly based on biofuels. However, the magnitude of the heat losses can be easily compared. The heat loss for the DN25 twin pipe was 14 W/m compared to the average annual heat loss of 9.7 W/m for the EPSPEX system. As mentioned earlier, laboratory studies indicate that the heat loss from an EPSPEX system might increase after repeated water soakings. An increase for the dried insulation with 43%, the worst case mentioned in the previous study [13], would result in an insulating capacity just below the DN25 twin pipe. This should be studied further.

The pump energy needed to circulate the water in the district heating system might differ between the EPSPEX system and the DN25 twin pipe system, but this has not been considered in this study.

These rough comparisons indicate that the EPSPEX system may provide a better environmental performance compared to conventional district heating pipes. A more detailed study with comparable pipe systems, preferably using conventional twin pipe dimensions corresponding to the ones used in this study, should be conducted. It should be borne in mind that

Table 4: Rough comparison of environmental impact assessment results for the EPSPEX system and the DN25 twin pipe system described in Fröling et al. 2004 and Fröling and Svanström 2005 [8,9]. A system life of 30 years has been assumed for both types of pipe network. Note that the systems are not exactly comparable in terms of function and that heat loss and sub-stations are not included

Production and network construction	Global warming potential (kg CO_2 eq./m, year)	Acidification potential (kg SO_2 eq./m, year)	Use of finite resources (kg resource eq./m, year^2)	EcoIndicator 99 (Ecopoints/m, year)
EPSPEX	0.78	0.0068	0.0092	0.086
DN25 twin [8,9]	1.1	0.0098	0.010	0.10

the EPSPEX system has some technical restrictions that do not apply to conventional pipes. EPSPEX is a low pressure system and can only be used in well drained ground above the water table, since the EPS foam has an open cell structure that otherwise will be water filled. There are also indications that the insulation capacity can be permanently decreased after repeated immersion in water [13,14]. It should also be noted that to date, there have been no long-term evaluations of the EPSPEX system. In the study of the DN25 twin pipes mentioned above, a life of 30 years has been assigned to the system in accordance with industrial standard requirements for the production of district heating pipes [10]. However, the life of a steel pipe distribution system for district heat is probably longer. When basing calculations on 50 instead of 30 years, the results change in favour of the DN25 pipes. This should be considered in a more detailed comparative study.

3 Conclusions

The most important method of reducing the total environmental impact of the EPSPEX system is to increase its insulation capacity, regardless of the fact that the system is relatively well insulated compared to conventional systems. The environmental impact of the total life cycle of the system is dominated by the impact of the production of the additional district heat needed to compensate for heat loss. District heat production with a lower environmental impact would also provide a relatively large environmental improvement, despite the fact that in the studied case, the district heat production is for the most part based on biofuels with a relatively low environmental impact. Note that there are some uncertainties regarding the heat losses of the EPSPEX system due to the fact that, at present, there are no long-term measurements available to validate calculated heat losses.

The fact that the space heating circuit of the EPSPEX system is turned off during the summer, leaving only the tap hot water circuit, results in a significant decrease in heat loss. The environmental impact of the operation of the system would otherwise be considerably higher.

Of the EPSPEX system components, production and transport of the EPS blocks had the largest environmental impact. It is therefore vital to utilize the material as efficiently as possible in order to minimize losses. The environmental impact due to the production of insulation is, however, more than compensated for by the decreased environmental load due to lower heat loss. Thus it is important to maintain the insulation capacity of the EPSPEX system in future product development.

The machines used for excavation run on diesel, and several characterisation and weighting methods show that the refining and combustion of this diesel has a considerable environmental impact. To reduce the size of the excavation as far as possible, in combination with the use of compact excavators and low-emission working vehicles, is therefore recommended.

In spite of the low weight share of the couplings in the system, the brass swaged coupling used to joint the PEX pipes has a large impact in terms of acidification potential and when the EPS 2000 weighting method is used. Swaged couplings from recycled brass or other materials would be worth investigating.

The second scenario which includes sub-stations would lead to a minor increase in the characterisation results for the construction related activities (i.e. system components and excavation) in all of the characterisation methods employed.

A rough comparison of the EPSPEX system with conventional DN25 twin pipes indicates that the environmental impact from the EPSPEX system is probably lower. A more detailed comparative study should be performed before reaching a final conclusion. It is important to bear in mind that the two systems have different technical applications. The PEX pipes cannot be used at as high temperatures and pressures as the steel pipe system. Another limitation is that the EPSPEX system can only be used above the ground water table.

4 Recommendations and Perspectives

In Sweden, new types of pipes are being developed for district heating in suburban areas, and there is a need for an environmental comparison between such new alternatives and previous results for conventional polyurethane insulated steel pipes. This study reveals that biofuels, although perceived to be environmentally friendly, must be used with caution in order to ensure a satisfactory environmental performance. Heat loss from district heating should also be minimized when biofuels are used. The most immediate way to reduce such environmental impact is to increase the insulation. The environmental trade-off between lower heat losses achieved by the use of more insulation and the production of greater amounts of insulation material should be further studied.

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